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NIVATION FORMS AND PROCESSES IN UNCONSOLIDATED SEDIMENTS, NE GREENLAND

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ABSTRACT

In the periglacial unconsolidated sediment landscape of Zackenberg in High Arctic NE Greenland, perennial and seasonal snowpatches dominate the geomorphological development in large areas and control the distribution of the vegetation. The existence and distribution of snowpatches and their associated landforms are mainly controlled by the dominating winter wind direction and the amount of snow precipitation, with aspect exerting much less influence. This makes them an important source of information on past environmental change, and knowledge of the combination of geomorphological processes and forms that result from their existence is thus essential.

The main nivation processes are backwall failure, sliding and flow, niveo-aeolian sediment transport, supra- and ennival sediment flows, niveo-fluvial erosion, development of pronival stone pavements, accumulation of alluvial fans and basins, and pronival solifluction. The importance of failure, sliding and flow in the continuous retrogressive extension of nivation hollows and niches is emphasized under the term backwall failure. A morphological assemblage of landforms clearly demonstrates the direct nival sediment transfer link between the eroded nivation hollows, their associated meltwater eroded channels and the pronival alluvial fans or basins. All landform elements and their formative processes are integrated into a comprehensive model. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: nivation; nivation hollows; active layer interflow; sedimentation in nivation hollows; nival backwall failure; pronival stone pavements; pronival alluvial fans; Greenland.

INTRODUCTION

At present snow covers 15 to 50 per cent of the entire land surface of the Earth depending on season (Schumskii, 1957). In High Arctic periglacial landscapes, perennial and seasonal snowpatches largely control the geomorphological development and the distribution of the vegetation. Detailed investigations of active geomorphological nivation processes caused by annual accumulation and ablation of snowpatches and the associated landforms in the High Arctic are thus essential. The use of fossil nivation landforms and sediments for palaeoenvironmental reconstructions, also in former periglacial areas, demands more information on nivation landform–climate relationships.

The concept of nivation was defined in 1900 by Matthes, as the process of backward erosion at the steeper portions of a snowdrift site caused by freeze–thaw at the edge of the snowdrift, and subsequent loosening and downward transport of the loose material. In most later literature this initial definition has been adopted (Christiansen, 1996a). But Thorn (1988) finds nivation to be a complex term, precluding a viable operational definition of nivation as a process term. However, the wide occurrence of snow and the associated nivation processes in periglacial landscapes call for a common concept, parallel to the concept of glaciation (Christiansen, 1996a). Nivation should encompass the many individual forms, processes and sediments associated with and intensified by the presence and disappearance of snow and particularly by perennial and seasonal snowpatches (Christiansen, 1996b). Defined in this way nivation spans large diversity, and is a process association, responsible for the geomorphologic development of large parts of past and present periglacial landscapes (Christiansen, 1996b).

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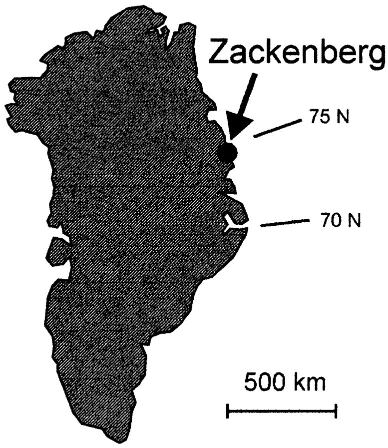

Figure 1. Location of the Zackenberg area in Greenland

Traditionally, nivation forms and processes have primarily been described from bedrock environments (Christiansen, 1996b), although they presumably are much more well developed and effective in unconsolidated sediment landscapes, as demonstrated in this paper.

THE ZACKENBERG STUDY AREA

The Zackenberg area (74°30′N, 20°30′W) is located in the ice-free area of High Arctic NE Greenland (Figure 1), about 30 km from the outer coast. Here the mountain Aucellabjerg (965 m a.s.l.) consists of Cretaceous sandstone capped by Tertiary basalts, with a cover of glacial sediments and distinctive moraine hills reaching up to about 400 m a.s.l. Southwest of Aucellabjerg, in the Zackenberg lowland, a glacial landscape with moraine ridges, ground moraine, meltwater plains and a large delta with several terraces exists. The area was last deglaciated at about 10 to 9 ka BP, with the large Zackenberg Delta being built at about 6·9 ka BP (Christiansen and Humlum, 1993). The area lies in the zone of continuous permafrost, with an active layer thickness of about 60 cm (Christiansen, 1997a). Mean annual air temperature is –9·8°C, and the annual precipitation is 223 mm (Humlum, 1997). Almost all precipitation falls as snow, primarily during the winter, when northerly winds dominate (Humlum, 1997). Data for the 1995–1996 period come from a new meteorological station in the Zackenberg Valley.

PHYSICAL CONDITIONS OF SNOWPATCHES

Large perennial and seasonal snowpatches lie in topographically conditioned lee positions on south-facing slopes, primarily on the south side of moraine ridges and along edges of fluvial terraces. Their distribution is mainly controlled by the prevailing northerly winter winds, while aspect, although controlling the amount of incoming radiation, exerts less influence. This shows the location of the snowpatches to be primarily controlled by the amount of precipitation and the dominant wind direction, thus emphasizing their palaeoclimatic value.

Each snowpatch has a basal ice layer due to the existence of continuous permafrost. Basal snowpatch temperatures of –10 °C to –11 °C were recorded from early December 1995 to early June 1996 in a representative snowpatch (Christiansen, 1997b). During summer the snowpatches, together with the development of the active layer, provide the primary source and control of water discharging from the ice-free areas to the otherwise semi-arid landscape.

In the areas at and around the snowpatches vegetation zones are controlled primarily by the timing of the snowmelt, and the more or less permanent release of meltwater from the snowpatches into the pronival zone during a significant part of the summer. A characteristic succession of heath and snow-related plants associated

Figure 2. A complete nivation form assemblage associated with a seasonal snowpatch. The nivation hollow is about 50 m wide. Several shallow meltwater drainage channels without vegetation lead from the snowpatch to an alluvial fan, where the person is standing. Aucellabjerg, 4 July 1996

with the snowpatches in the Zackenberg area have been described by Fredskild (1992), reflecting the critical length of the growing season in various parts of the nivation hollows.

NIVATION FORM ASSEMBLAGE

In early summer, the snow cover melts quickly, leaving snowpatches only where wintertime snow accumulation has been favoured by topoclimatic factors. Around the snowpatches a characteristic assemblage of erosional, transportation and depositional landforms can develop, controlled by a combination of lithology, topography and nivation process rates. In Zackenberg the dominating form assemblage consists of a nivation hollow or depression, from 50 to 500 m wide, containing a perennial or seasonal snowpatch (Figure 2). Downslope of the snowpatch there is an associated zone of meltwater erosion with furrows or channels, sometimes ending in a depositional fan or basin, where sediments accumulate (Figure 2). Nivation hollows are erosional landforms, formed as depressions in sloping terrain, often with a semi-circular shape open in the downslope direction.

The pronival zone is the zone being gradually exposed during summer in front of the snowpatches, with distinct vegetation zones controlled by the backmelting of snow and the length of the growing season. In this area the primary nival impact is gradual subaerial exposure, and the continuous flow of meltwater, leading to the development of stone pavements, solifluction sheets and alluvial fans. The lower limit of the pronival zone is often gradual. It is located where the nival impact is no longer visible and where the surrounding, semi-arid vegetation, not influenced by nivation, starts to grow.

Topography and lithology are fundamental constraints on the development of a complete nivation form assemblage. Where the slope below a snowpatch is steep and there is no topographical depression, nival sediments will be transported a long distance away and mixed with other, typically fluvial, sediments. From some large snowpatches, nival meltwater streams run several kilometres into the large Zackenberg River. In such situations no evident nival depositional landforms exist and it is very difficult directly to detect the sediment coming from a specific snowpatch. Likewise, in the bedrock areas in Zackenberg, nival erosion is too slow for distinctive nivation niches to develop and nivation form assemblages therefore are often non-existent or only weakly developed. However, complete nivation form assemblages do exist, and they are especially well developed on the southwest-exposed slopes of the Aucellabjerg, where dominance of unconsolidated Cretaceous sandstone and glacial sediments enhance nival erodibility.

SEDIMENT SUPPLY TO SNOWPATCHES AND NIVATION HOLLOWS

Drifting snow and niveo-aeolian sediment incorporation into snowpatches

Niveo-aeolian sediment is defined as a mixture of wind-deposited snow, sand, silt, vegetational and other debris (Cailleux, 1978). Silt and sand are lifted and become suspended into the drifting snow, when ice crystals at the ground surface sublimate (Schwan, 1986). Experiments have shown that sediment release by sublimation is most successful when the sediment is weakly cemented and very cold (McKenna Neuman, 1989). Niveo-aeolian sediment transport is maximal when the amount of snow in the landscape is moderate (Schwan, 1986). Thus the semi-arid Zackenberg area, with an incomplete and discontinuous winter snow cover, should support niveo-aeolian sediment transport.

Sediments are especially eroded by drifting snow from surfaces without vegetation, such as the large fluvial bars dominating the central Zackenberg Valley area, and the tops of moraine ridges, and transported onto and subsequently into the snowpatches. Active deflation surfaces with well developed wind-abraded surfaces of stones and boulders indicate the effect of drifting snow and/or sediment very clearly. Snowdrift is generally found to take place even at low, persistent wind speeds of 3–4 $m\,s^{-1}$ (measured at 2 m above terrain) (Christiansen, unpublished results). The dominating southerly snowpatch aspect shows that northerly winds are controlling the snowdrift and thus the accumulation of snowpatches. The rate of niveo-aeolian sediment transport is therefore dependent primarily on a proper sediment source area in the upwind direction. The distance that snow particles can travel varies between 500 and 1400 m, according to particle size, particle velocity, air temperature, relative humidity and total insolation (Tabler and Schmidt, 1972). Source areas for niveo-aeolian sediment are, however, generally located with 500 m of the snowpatch. In 1995/96 the winter surface temperature on a deflation surface in the Zackenberg area was below −22 °C for long periods, which was the lower temperature limit in the experiments carried out by McKenna Neuman (1989), as described earlier. Therefore it appears likely that niveo-aeolian sediment transport is favoured in the Zackenberg area.

Sedimentation in nivation hollows

The intense ablation of snowpatch surfaces during summer causes a concentration of sediments on the snowpatch surface. Melting rate is accelerated by a patchy, thin sediment cover, but retarded by a thick sediment cover. This differential downmelting of the snowpatch causes accumulation and sedimentation on the snowpatch surface of some very unstable small-scale forms, such as fans, ridges and flows, varying from only some centimetres to about 1 m in diameter or length.

Along the margins of downmelting snowpatches, continuous deposition of quasi-stationary small-scale sedimentary landforms can lead to a rather extensive, but often temporary, covering of the seasonally exposed snowpatch bed. These nival deposition processes and landforms are to some degree small-scale parallels to the supraglacial deposition processes and landforms accumulating during areal downwasting of debris-covered glaciers. Downslope of the backmelting snowpatch, most of the deposited sediments are transported away by meltwater from the nivation hollow to the pronival area. The rest of the deposited sediment can either be blown out of the nivation hollow during the following autumn before the snowpatch is established again, or become incorporated in nival backwall failure activity (see below). Some sediment will stay in the nivation hollow, leading to partial refilling, primarily in the upper part.

The rate of sedimentation in the nivation hollows depends primarily on the existence of sediment source areas, supplying sediment to the snowpatches by niveo-aeolian transport or by the erosion processes described in the next section. Likewise, the extent of niveo-fluvial sediment transport is controlling the amount of sediment left in nivation hollows. If sedimentation on the backwall of a nivation hollow is large, the hollow will be only shallow, and the primary nival geomorphological imprint is the small, shallow pronival drainage channels. Snowpatches without a large sediment supply, and no nival sedimentation, are often located in well developed, deep nivation hollows, showing them to be primarily formed by erosional processes.

Nivation hollows with seasonal snowpatches receiving much sediment, but with no backwall failures (see below), span the largest diversity of vegetation zones. They possess, in particular, a central zone where only pioneer plants can grow, due to the constant supply of sediment covering the terrain surface and the short growing season. At perennial snowpatches, where the central zone of the nivation hollows is always covered by

Figure 3. Large-scale rotational backwall failure, with slides and flows. The steep backwall of the nivation hollow is about 2–3 m deep. The surrounding terrain and the upper parts of the failure were already completely dry on 16 July 1996. Aucellabjerg

snow, a zone without any vegetation exists below the snowpatch. At seasonal snowpatches where deposition is not so significant, the entire bottom of the nivation hollow is often covered by a homogenous vegetation.

NIVAL EROSION AND SEDIMENT TRANSPORT AT SNOWPATCHES

Nival backwall failure

Retrogressive slope failures, slides and flows taking place at the backwall of nivation hollows, collectively termed backwall failures, are primarily responsible for the expansion of nivation hollows. They occur as rotational block slumps when snowpatches melt away from the backwall during summer (Figure 3). Failure activity can occur at backwalls sloping no more than 2° to 5°, and with a drainage area located above the snowpatch. The maximum size of the blocks observed to rotate was 0·5 m thick and 3 m in height. The thin vegetation layer is destroyed by sliding, revealing diamict. Removal of the active layer in some places exposes the permafrost table, causing thermal degradation of the permafrost. This leads to a constant retrogressive movement of the permafrost table, with increased backwall failures. Backwall failure activity leads to the development of a characteristic, reasonably continuous trimline, along the upper limit of slumps and slides, indicating the maximum early summer snowpatch extension. Some of the small slumps at the snowpatch backwalls are due to exposure of ice wedges, which produce nearly gully-like sliding forms.

Measured profiles of active layer thickness from above upper backmelting snowpatch limits, show the active layer thickness to decrease towards the snowpatch edge (Figure 4). This was also observed by Poser (1932) and Thomas (1981) in central East Greenland. Meltwater from the developing active layer drains downslope in the active layer as interflow towards the upper snowpatch limit, mainly controlled by the topography of the permafrost table. The active layer interflow is forced to the ground surface at the uppermost part of the snowpatches, where the active layer has not yet developed. It is presumably this mechanism that is primarily responsible for initiating the sliding activity, emphasizing the close relationship between active layer slides and snowpatches in the Zackenberg area that lead to the coining of the term ‘nival backwall failures’.

The saturation of the active layer above the snowpatches raises pore water pressure in a zone immediately above the upper snowpatch edge. Slopes then become unstable, with failure planes located at the permafrost table, on which the saturated active layer sediment slumps, slides and flows. Failure takes place until backmelting of the snowpatch improves drainage at the backwall.

Nival backwall failure is a self-intensifying process and it dominates the development and expansion of nivation hollows. Controlling factors are the supply of active layer interflow streaming towards the snowpatch, combined with the inclination of the backwall, and the texture of the sediment.

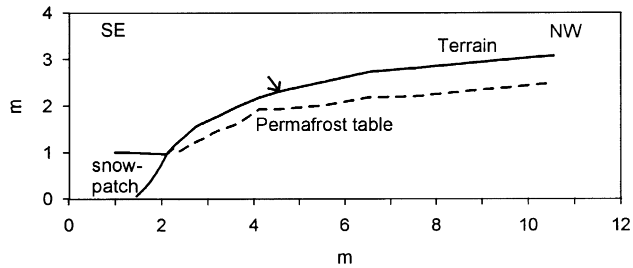

Figure 4. Typical active layer thickness profile from the upper backwall of a nivation hollow, with active backwall failure, and up onto the surface upslope. The upper nivation hollow with a backmelting snowpatch is schematically shown below the reduced active layer. The arrow marks the upper limit for failure activity. Measured on 27 June 1996 in the Zackenberg lowland

An important hydrological consequence of the nival-controlled active layer interflow accumulation is that the snowpatches act as surface runoff outlets for interflow water from neighbouring active layers and thus sustain runoff from the lower margins of the snowpatches, as described by Ballantyne (1978). This process of drainage from the active layer upslope significantly enlarges the otherwise snowdrift-delimited ‘catchment’ areas responsible for the accumulation of snow in the snowpatches, and thus also increases the discharge from the snowpatches to the pronival environment.

If the extent of a snowpatch is diminished one year, failure activity may take place farther downslope in the nivation hollow compared to preceding years. In years with enlarged snowpatches, the opposite can happen, and failure then takes place upslope of the nivation hollow proper, revealing the extreme extent of the snowpatch. Therefore, as the development and extension of nivation hollows are largely controlled by backwall failure, the morphology of nivation hollows is very sensitive to changes in the controlling meteorological conditions, which are the amount of winter snow precipitation and/or the prevailing winter wind direction and speed. Consequently, the evolution of nivation hollows may indicate changing wintertime meteorological conditions, such as the amount of accumulation and/or relocation of ‘lee’ locations as snow-bearing wind directions change, but may also reflect changes in summertime (ablation) conditions, primarily by adjustments in size. Responses to accumulation and ablation variations may be convergent.

Supra- and ennival sediment flows

Sediment delivery to the supra- and ennival environments in late spring and summer originates from backwall slides. Due to total water saturation, backwall slides are often mudslides which flow onto the snowpatch. This sediment is augmented by summertime delivery of material by rill flow and concentrated overland flow starting on the hillslope above the snowpatch. The meltwater for such flows is primarily from rapid melting of the winter snow cover upslope of the snowpatch proper.

In the supranival environment, the flow of sediment leaves significant morphological imprints such as channels and sheet-like, patchy covers of sediment. Sediment is transported through the channels in suspension and deposited as sheets of sediment on the snowpatch surface. Some channels are ennival for some distance before penetrating to the bottom of the snowpatch. In places, small ablation cones develop where the sediment cover is thick and prevents the snow beneath from melting. Levees indicate that large amounts of water and sediment have been eroding the channels during short events of maximum snow ablation, typical for the early summer when the more continuous snow cover melts.

The supranival material also contains large amounts of organic matter. Supranival meltwater streams can carry small tussocks onto the snowpatch, indicating their erosive power. Most supra- and ennival flow material is finally transported by the meltwater out of the nivation hollows as the snowpatches gradually melt.

Pronival solifluction

The short snowpatch ablation period in the High Arctic causes a concentrated summer discharge of meltwater to the pronival areas, with large geomorphological effects outside the nivation hollows. Meltwater soaks the ground in front of the lower snowpatch edge, leading to sheetwash and flow of sediment away from the snowpatch, while farther downslope solifluction dominates.

Figure 5. Stone pavement below a nivation hollow with backwall failure activity. This stone pavement is particularly well developed as snow meltwater runs from higher areas through it. The height of the backwall is about 4 m, and about 30 m of the stone pavement zone is seen. 14 July 1996, Zackenberg lowland

During snowmelt the upper pronival zone is totally water saturated, and small shallow channels are eroded into both bare and vegetated terrain surfaces immediately downslope of the snowpatches. Some of these channels are fed directly from channels eroded thermally into the basal ice layer of the lower snowpatch. In these channels the content of sediment transported in suspension varied between 1378 and 4523 mg l^{-1}, in a few samples taken immediately downslope of backmelting basal ice layers. This demonstrates that large amounts of sediment are being supplied to the pronival zone with the meltwater. The active layer is seen to flow as large solifluction sheets, some more than 100 m long, downslope in the pronival zone.

Pronival stone pavements

Well developed stone pavements, free of vegetation, exist in the inner parts of the pronival zone at several snowpatches (Figure 5). They resemble glacial surface pavements of stone. In the Wollaston Forland area, about 30 km from the Zackenberg area, Poser (1932) has described similar features associated with snowpatch areas. Stone pavements more than 50–100 m wide, comprising stones from 10 cm to 1 m in diameter, are seen in late summer constituting the inner pronival zone. They are associated with either large snowpatches or those receiving meltwater from snowpatches located farther upslope, thus increasing the amount of meltwater available for niveo-fluvial erosion.

The development of stone pavements seems to be primarily due to erosion of fine-grained sediment by percolating meltwater from the snowpatch. This process was also held responsible for the development of boulder pavements in the alpine subnival environment (Hara and Thorn, 1982). Likewise, the weight of the snowpatch appears to be important in embedding the stones in the matrix. The distal limit of the pronival stone pavement indicates the maximum snowpatch position in late spring, when ablation of the snowpatches starts, as found in Norway (Hall, 1980).

Pronival alluvial fans and basins

Downslope of some snowpatches, alluvial fans and basins accumulate where the meltwater flows over a low gradient, or where the terrain slopes towards the front of the snowpatch in the pronival zone. Where nivation is continuous, alluvial fans and basins are constantly developing and are devoid of any vegetation, or covered by vegetation only in the lower parts where sedimentation is more sporadic.

The fans are growing depositional sheets of sediment, controlled by meltwater discharge and sediment availability from the snowpatch. Their stratigraphy comprises horizontal layers, 0·01 to 5 cm thick, of clay and

Figure 6. Nivation dominating the geomorphological development of the lower 250 m of Aucellabjerg, Zackenberg. Snow meltwater has eroded channels more than 1 m deep and several metres wide. This is possible as more and more meltwater crosses the lower part of the mountain. Between the channels large solifluction sheets extend from one nivation hollow to the next. The area in the photo is about 1 km wide. 2 July 1996

silt, sand or gravel. This largely reflects the individual meteorological events during the snowpatch ablation period. Clear sky conditions, with large amounts of insolation, cause intense melting, leading to deposition of sand and gravel, but also to some erosion and resedimentation on the alluvial fans. In overcast and cold conditions, only a little meltwater is produced and primarily fine-grained sediment is deposited. As a parallel to the described nival fans and basins, observations of the accumulation of nivation sediment as cones have been presented by Catto (1993) and by Berglund and Rapp (1988).

NIVATION CONTROLLING THE GEOMORPHOLOGICAL DEVELOPMENT IN LARGER AREAS

Major areas of the lower unconsolidated Aucellabjerg landscape, below about 600 m a.s.l., are affected by nivation (Figure 6). This shows the large areal extent of particularly pronival processes and landforms, and how they can interact in larger areas.

Meltwater draining from snowpatches assists in shaping nivation hollows located downslope. Linear enhanced meltwater erosion causes the development of numerous niveo-fluvial channels (Figure 6), running through nivation hollows and successively dissecting particularly the pronival lower slopes. The drainage system on the entire mountain side is completely controlled by the meltwater streaming from the snowpatches. Boulder pavements occur in the pronival environment and at the bottom of the braided watercourses in the niveo-fluvial channels eroded downslope from the snowpatches. They are best developed at nivation assemblages at lower elevation, as these receive most meltwater, and here also significant solifluction activity takes place. Solifluction sheets extend from one snowpatch to the next, with backwall failures marking the transition to the lower snowpatch. In this way solifluction as a pronival process becomes competitive with the nival backwall failure processes, showing the complete dominance of nivation processes and landforms on this mountain side.

A NIVATION PROCESS–FORM–SEDIMENT MODEL FOR UNCONSOLIDATED SEDIMENTS

The description of the primary nival processes and forms enables creation of a comprehensive snowpatch process–form–sediment model for nivation in the Zackenberg area (Figure 7). This should apply in most

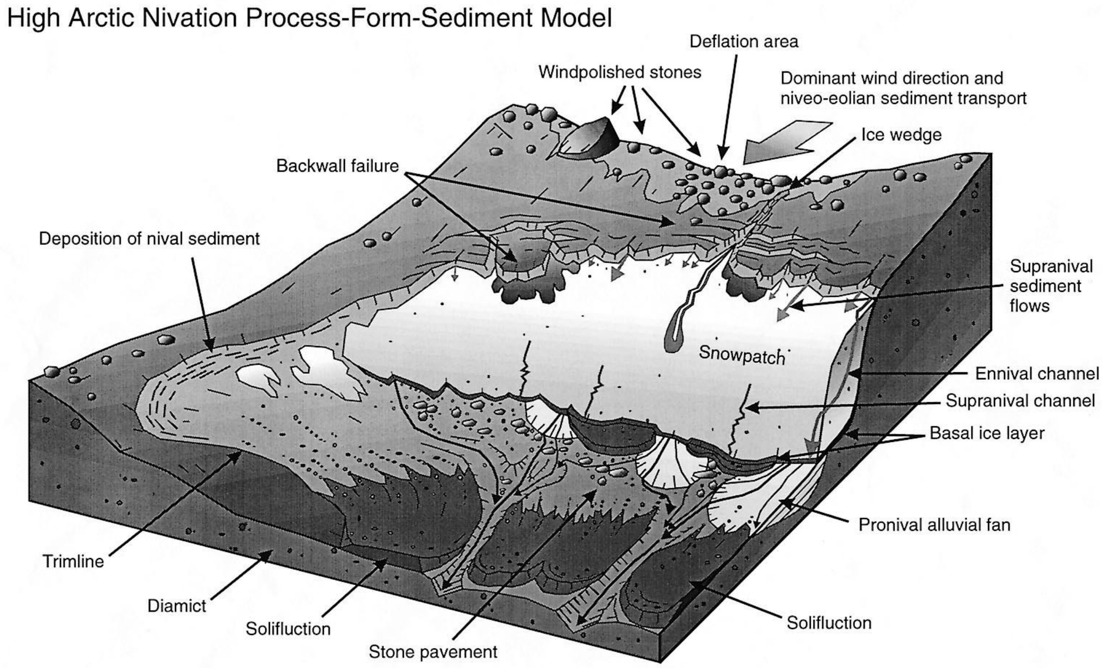

Figure 7. The geomorphological High Arctic nivation process–form–sediment model as established for unconsolidated sedimentary landscapes based on the presented observations from the Zackenberg area in NE Greenland. The model shows a late summer situation with a simplified perennial snowpatch in a nivation hollow. The dominant nivation processes and landforms, as described in the text, are shown

periglacial landscapes consisting of unconsolidated sediments, with continuous permafrost and where precipitation primarily falls as snow.

The model is, on the large scale, controlled by environmental conditions, the dominant ones being the prevailing snow-bearing wind direction, winter wind speed and the amount of precipitation falling as snow. Amounts of active layer interflow water and the different sizes of snowdrift catchment areas are also important. Thus the model explains the initiation and development of nivation hollows by nivation processes being controlled primarily by local climatic and topographical conditions.

On a smaller scale, the development of individual nivation hollows and complete nivation assemblages is dependent on the balance between the different nivation processes. During winter, niveo-aeolian sediment transport is the dominant process supplying sediment to the snowpatches. Very erosive backwall failure is the key process for the maintenance and extension of nivation hollows. It is the principal mechanism responsible for the removal of sediment from the backwall and a source of sediment being transported into the supra- and ennival environments during summer. If there is no or only little backwall failure activity, resedimentation of primarily niveo-aeolian sediment can lead to partial filling of the nivation hollows. Pronival solifluction, development of stone pavements and deposition of alluvial fans and basins in the pronival zone are the characteristic geomorphological processes and landforms resulting from snowpatch ablation.

To determine whether the presented nivation form assemblage is in equilibrium, degrading once it reaches a certain size, or continuously increasing through time, a quantification of all nivation process rates is necessary. However, use of the nivation model, in combination with detailed studies and dating of the sediments in nival-alluvial fans or basins (Christiansen, 1996b, submitted) permits reconstruction of palaeonivation events. This allows dominating palaeowind directions and periods of snowdrift activity to be reconstructed. For these reasons the establishment and further improvement of the nivation process–form–sediment model are important and necessary to understand the recent, but also former geomorphological development, in large parts of periglacial landscapes. Finally, the model can provide a basis for understanding the geomorphological

effects of potential changes in snow fall and dominating winter wind direction caused by possible climatic changes or modelling of such changes.

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